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Study of the pionic enhancement in $^{16}\text{O}(p, p')^{16}\text{O}(0^-, T = 1)$ at 295 MeV

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Abstract

The cross section of the $^{16}\text{O}(p, p')^{16}\text{O}(0^-, T = 1)$ scattering was measured at a bombarding energy of 295 MeV in the momentum transfer range of $1.0 \text{ fm}^{-1} \leq q_{\text{c.m.}} \leq 2.1 \text{ fm}^{-1}$. The isovector 0^- state at $E_x = 12.8 \text{ MeV}$ is clearly separated from its neighboring states owing to the high energy resolution of about 30 keV. The cross section data were compared with distorted wave impulse approximation (DWIA) calculations employing shell-model wave functions. The observed cross sections around $q_{\text{c.m.}} \simeq 1.7 \text{ fm}^{-1}$ are significantly larger than obtained by these calculations, suggesting pionic enhancement as a precursor of pion condensation in nuclei. The data are well reproduced by DWIA calculations using random phase approximation response functions including the Δ isobar that predict pionic enhancement.

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Keywords: Isovector 0^- state; High resolution measurement; Pionic enhancement; Spin-longitudinal response; Landau–Migdal parameters

The search for pionic enhancements in nuclei has a long and interesting history. These phenomena can be considered as a precursor of the pion condensation [1] that would be realized in neutron stars. Enhancements of the M1 cross section in proton inelastic scattering [2–5] and of the ratio R_L/R_T , the spin-longitudinal (pionic) response function R_L to the spin-

transverse (non-pionic) response function R_T , in the quasi-elastic scattering (QES) region [6,7] were expected around a momentum transfer $q_{\text{c.m.}} \simeq 1.7 \text{ fm}^{-1}$. However, experimental data such as the differential cross section of the M1 transition $^{12}\text{C}(p, p')^{12}\text{C}(1^+, T = 1)$ [8] and the ratio R_L/R_T extracted from ^{12}C , $^{40}\text{Ca}(\vec{p}, \vec{n})$ [9,10] did not reveal any enhancements, and they were considered as evidences against the precursor phenomena of the pion condensation in normal nuclei. Several explanations exist to answer the question why no pionic enhancements were observed. For example, Bertsch et al. [11] suggest the modification of gluon properties in the nucleus that suppresses the pion field. Brown et al. [12] suggest the par-

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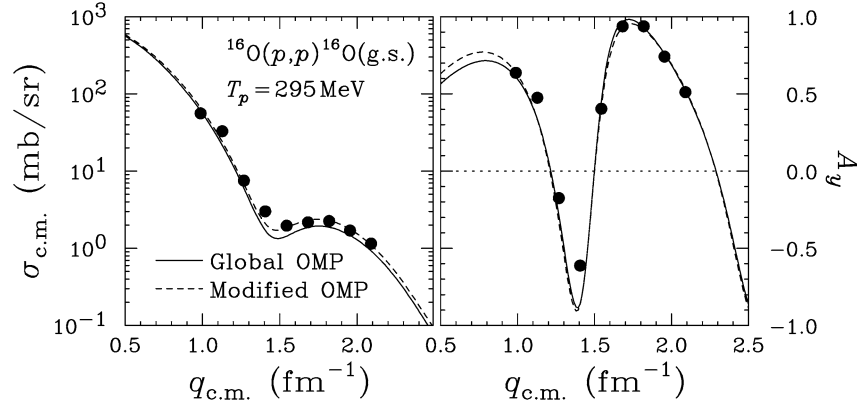


Fig. 1. The measurement of the cross section (left panel) and the analyzing power (right panel) for $^{16}\text{O}(p, p)$ at $T_p = 295$ MeV. The solid curves are the theoretical predictions using the global OMP for ^{16}O . The dashed curves represent the results with the modified OMP as explained in the text.

tial restoration of chiral invariance with density. However, we should note that the M1 cross section involves both the pionic and the non-pionic transitions, and similarly the non-pionic response R_T is equally important to determine the ratio R_L/R_T . Thus, in these indirect measurements, the pionic enhancement might be masked by the contribution from the non-pionic component. Recent analysis of the QES data [13] shows a pionic enhancement in the spin-longitudinal cross section that well represents the R_L , and suggests that the lack of enhancements of R_L/R_T is due to the non-pionic component.

In order to measure the pionic enhancement directly, it is desirable to investigate isovector $J^\pi = 0^-, 0^\pm \rightarrow 0^\mp$ excitations because they carry the same quantum numbers as the pion and they are free from non-pionic contributions in the direct channel. Orihara et al. [14] measured the angular distribution of the $^{16}\text{O}(p, n)^{16}\text{F}(0^-)$ reaction at $T_p = 35$ MeV. They reported discrepancies between distorted wave Born approximation calculations and their data in the range of $q_{\text{c.m.}} = 1.4\text{--}2.0$ fm^{-1} that might be a signature of pionic enhancement. However, in both the $^{16}\text{O}(p, p')^{16}\text{O}(0^-, T = 1)$ scattering at $T_p = 65$ MeV [15] and the $^{16}\text{O}(p, n)^{16}\text{F}(0^-)$ reaction at $T_p = 79$ MeV [16], such an enhancement was not observed. The differences in these (p, n) and (p, p') results might indicate contributions from complicated reaction mechanisms at these low incident energies. To our knowledge, there are no published experimental data for the $0^-, T = 1$ state at intermediate energies of $T_p > 100$ MeV where reaction mechanisms are expected to be simple.

In this Letter, we present the measurement of the cross section for the excitation of the $0^-, T = 1$ state at $E_x = 12.8$ MeV in ^{16}O using inelastic proton scattering at 295 MeV incident energy. The results are compared with distorted wave impulse approximation (DWIA) calculations using shell-model (SM) wave functions. A possible evidence of the pionic enhancement is observed from a comparison between experimental and theoretical results. The data are also compared with DWIA calculations employing random phase approximation (RPA) response functions including the Δ isobar in order to assess the pionic enhancement quantitatively.

The measurement was carried out by using the west-south beam line (WS-BL) [17] and the Grand Raiden (GR) spectrom-

eter [18] at the Research Center for Nuclear Physics, Osaka University. The WS-BL provides the beam with lateral and angular dispersions of 37.1 m and -20.0 rad, respectively, which satisfy the dispersion matching conditions for GR, necessary for high momentum and angle resolutions. The beam bombarded a windowless and self-supporting ice (H_2O) target [19] with a thickness of 14.1 mg/cm^2 . Protons scattered from the target were momentum analyzed by the high-resolution GR spectrometer with a resolution of about 30 keV FWHM. The beam energy was determined to be 295 ± 1 MeV by using the kinematic energy shift between elastic scattering from ^1H and ^{16}O . The yields of the scattered protons were extracted using the peak-shape fitting program ALLFIT [20].

The elastic differential cross sections on ^{16}O are shown in the left panel of Fig. 1. They were normalized to the known $p + p$ cross section [21] by utilizing the data of protons scattered from ^1H in the ice target. The analyzing power was also measured and the results are shown in the right panel. The data were analyzed by phenomenological optical model potentials (OMPs). The solid curves in Fig. 1 are the results using the global OMP optimized for ^{16}O [22]. The dashed curves represent the results with the modified real and imaginary spin-orbit potentials by a factor of 1.15. The modified OMP gives a better description of our data especially for the cross sections at large momentum transfers.

Fig. 2 shows the excitation energy spectrum of the $^{16}\text{O}(p, p')$ scattering at $q_{\text{c.m.}} = 1.9$ fm^{-1} . The isovector 0^- state at $E_x = 12.8$ MeV is clearly resolved from the neighboring states. The dashed curves represent the fits to the individual peaks while the straight line and solid curve represent the background and the sum of the peak fitting, respectively. Narrow peaks of ^{16}O were described by a standard hyper-Gaussian line shape, and the peaks with intrinsic widths were described as Lorentzian shapes convoluted with a resolution function based on the narrow peaks. The positions and widths were taken from Ref. [23].

Fig. 3 shows the measured data points and the calculated curves of the cross sections of the $0^-, T = 1$ transition in $^{16}\text{O}(p, p')$ as a function of the momentum transfer $q_{\text{c.m.}}$. The angular distribution was measured in the range of $q_{\text{c.m.}} \simeq 1.0$ fm^{-1} to $\simeq 2.1$ fm^{-1} starting near the second maximum at $q_{\text{c.m.}} \simeq 0.9$ fm^{-1} and extending beyond the third maximum

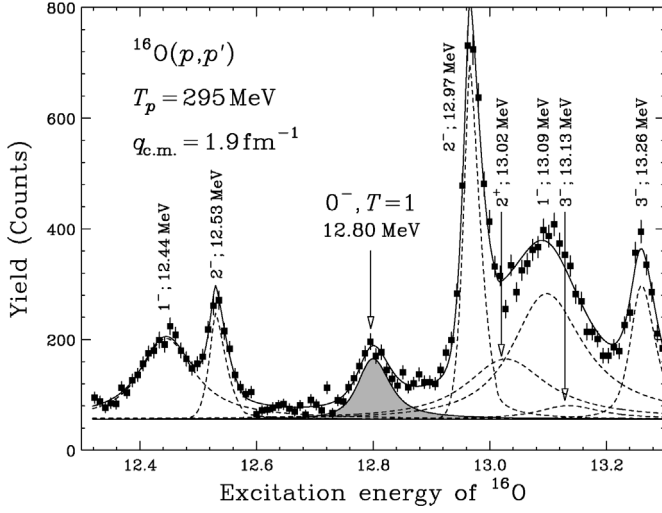


Fig. 2. The excitation energy spectrum for $^{16}\text{O}(p, p')$ at $T_p = 295$ MeV and $q_{\text{c.m.}} = 1.9 \text{ fm}^{-1}$. The curves show the reproduction of this spectrum with hyper-Gaussian and Lorentzian peaks and a continuum.

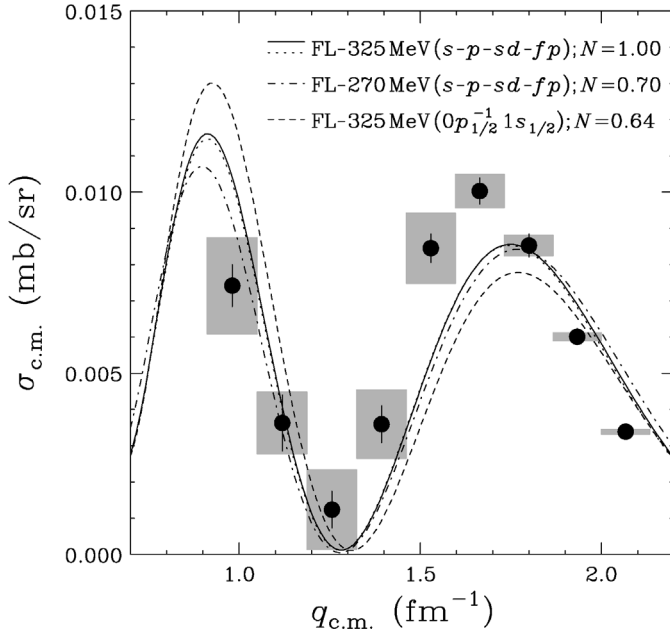


Fig. 3. The measurement of the cross section of $^{16}\text{O}(p, p')^{16}\text{O}(0^-, T=1)$ at $T_p = 295$ MeV. The solid (dash-dotted) curve is the DWIA result with the t -matrix parametrized at 325 (270) MeV employing the SM wave function in the $0s-0p-1s0d-1p0f$ model space. The dashed curve denotes the DWIA result with the t -matrix at 325 MeV employing the pure $0p_{1/2}1s_{1/2}$ SM wave function. The dotted curve represents the DWIA result with the modified OMP as described in the text.

at $q_{\text{c.m.}} \simeq 1.7 \text{ fm}^{-1}$. The data at $q_{\text{c.m.}} < 0.9 \text{ fm}^{-1}$ could not be measured because of the kinematic overlap with the $p + p$ events. The error bars of the data points are the fitting uncertainties originating from the statistical uncertainties. The shaded areas represent the systematic uncertainties including the background subtraction.

We performed DWIA calculations by using the computer code DWBA98 [24]. The one-body density matrix elements (OBDME) for the isovector 0^- transition of $^{16}\text{O}(p, p')$ were

obtained from SM calculations [25] which were performed in the $0s-0p-1s0d-0f1p$ configuration space by using phenomenological effective interactions. In the calculation, the ground state of ^{16}O was described as a mixture of $0\hbar\omega$ (closed-shell) and $2\hbar\omega$ configurations. The single particle wave functions were generated by a Woods–Saxon (WS) potential with $r_0 = 1.27 \text{ fm}^{-1}$ and $a_0 = 0.67 \text{ fm}^{-1}$ [26], the depth of which was adjusted to reproduce the separation energies of the $0p_{1/2}$ orbits. The unbound single particle states were assumed to have a very small binding energy of 0.01 MeV to simplify the calculations. The NN t -matrix parametrized by Franey and Love [27] at 325 MeV was used. The DWIA results with the global and the modified OMPs are shown as the solid and the dotted curves, respectively, in Fig. 3. The results are insensitive to the OMP, and thus we will use the global OMP in the following. None of the calculations reproduce the data. Especially, note the underestimation around the third peak, which appears at about $q_{\text{c.m.}} \simeq 1.7 \text{ fm}^{-1}$ in the experiment, but about $q_{\text{c.m.}} \simeq 1.8 \text{ fm}^{-1}$ in the calculation.

We investigated the sensitivity of the DWIA calculations to changes of the parameters involved. The dash-dotted curve represents the DWIA calculation with a different t -matrix parametrized at 270 MeV. The result is systematically larger compared to the calculation with the t -matrix at 325 MeV. The dash-dotted curve is, therefore, multiplied by a factor of 0.7. The dashed curve denotes the calculation employing a different OBDME with a pure $0p_{1/2}1s_{1/2}$ transition from the $0\hbar\omega$ (closed-shell) ground state. Auerbach and Brown [25] suggest that this isovector strength is quenched and spread by a $2\hbar\omega$ admixture. They obtained a quenching factor of ~ 0.64 . Thus we have multiplied our result by this factor. We also performed a DWIA calculation with the radial wave functions generated by a harmonic oscillator potential with a size parameter of $\alpha = 0.588 \text{ fm}^{-1}$ [28]. The result is systematically larger compared to the calculation with the WS potential. However, their shapes of the angular distribution are very similar to each other. From these calculations we found that the experimental data could not be reproduced well by changing the input parameters within the framework of the DWIA employing SM wave functions.

Therefore, we investigated the non-locality of the nuclear mean field by a local effective mass approximation [10] in the form of

$$m^*(r) = m_N - \frac{f_{\text{WS}}(r)}{f_{\text{WS}}(0)}(m_N - m^*(0)), \quad (1)$$

where m_N is the nucleon mass and $f_{\text{WS}}(r)$ is a WS radial form. The calculations were performed using the computer code CRDW developed by the Ichimura group [29]. The dotted and dashed curves in Fig. 4 show the DWIA results with the free response function employing $m^*(0) = m_N$ and $m^*(0) = 0.7m_N$, respectively. The 0^- component of the free response is configured as a pure $0p_{1/2}1s_{1/2}$ transition with a normalization factor of 0.64. The DWIA result with $m^*(0) = m_N$ is in good agreement with the calculation employing the corresponding SM wave function represented by the dashed curve in Fig. 3. Thus we have applied the same normalization factor of 0.64 to all the calculations shown in Fig. 4. The angular distri-

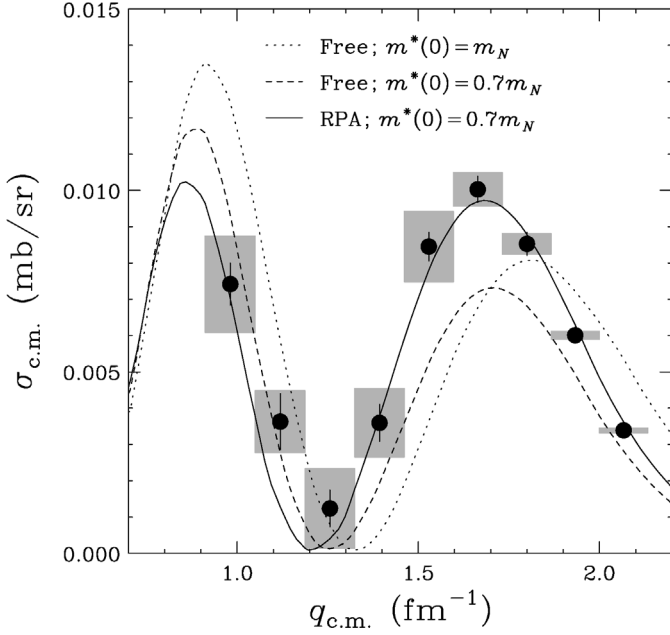


Fig. 4. Comparison between experimental and theoretical cross sections of $^{16}\text{O}(p, p')^{16}\text{O}(0^-, T = 1)$ at $T_p = 295$ MeV. The dotted and dashed curves represent the DWIA results with the free response function employing $m^*(0) = m_N$ and $m^*(0) = 0.7m_N$, respectively. The solid curve denotes the DWIA result employing the RPA response function with $g'_{NN} = 0.7$, $g'_{N\Delta} = 0.4$, and $m^*(0) = 0.7m_N$.

bution shifts to lower $q_{\text{c.m.}}$ when decreasing $m^*(0)$. A value of $m^*(0) \simeq 0.7m_N$ [30,31] improves the agreement with the data, especially for the angular distribution. However there is still a large discrepancy between experimental and theoretical results around $q_{\text{c.m.}} \simeq 1.7 \text{ fm}^{-1}$.

Considering these analyses, we finally discuss the RPA correlation and Δ effects. We performed DWIA calculations with the RPA response functions employing the $\pi + \rho + g'$ model interaction V_{eff} and the meson parameters from a Bonn potential which treats the Δ explicitly [32]. The interaction V_{eff} is the sum of the one- π and one- ρ exchange interactions, and the Landau–Migdal (LM) interaction V_{LM} specified by the LM parameters, g'_{NN} , $g'_{N\Delta}$, and $g'_{\Delta\Delta}$, as

$$V_{\text{LM}} = \left[\frac{f_{\pi NN}^2}{m_\pi^2} g'_{NN} (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) + \frac{f_{\pi NN} f_{\pi N\Delta}}{m_\pi^2} g'_{N\Delta} \{ ((\boldsymbol{\tau}_1 \cdot \boldsymbol{T}_2) (\boldsymbol{\sigma}_1 \cdot \boldsymbol{S}_2) + (\boldsymbol{\tau}_1 \cdot \boldsymbol{T}_2^\dagger) (\boldsymbol{\sigma}_1 \cdot \boldsymbol{S}_2^\dagger)) + (1 \leftrightarrow 2) \} + \frac{f_{\pi N\Delta}^2}{m_\pi^2} g'_{\Delta\Delta} \{ ((\boldsymbol{T}_1 \cdot \boldsymbol{T}_2) (\boldsymbol{S}_1 \cdot \boldsymbol{S}_2) + (\boldsymbol{T}_1 \cdot \boldsymbol{T}_2^\dagger) (\boldsymbol{S}_1 \cdot \boldsymbol{S}_2^\dagger)) + \text{h.c.} \} \right] \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2), \quad (2)$$

where $\boldsymbol{\sigma}$ ($\boldsymbol{\tau}$) is the nucleon Pauli spin (isospin) matrix, \boldsymbol{S} (\boldsymbol{T}) is the spin (isospin) transition operator that excites N to Δ , $f_{\pi NN}$ ($f_{\pi N\Delta}$) is the πNN ($\pi N\Delta$) coupling constant, and m_π is the pion mass. The LM parameters have been estimated to be $g'_{NN} = 0.7 \pm 0.1$ and $g'_{N\Delta} = 0.4 \pm 0.1$ [13]. The solid curve in

Fig. 4 shows the DWIA result with $g'_{NN} = 0.7$, $g'_{N\Delta} = 0.4$, and $m^*(0) = 0.7m_N$. This calculation reproduces the experimental data reasonably well. It shows large enhancement around $q_{\text{c.m.}} \simeq 1.7 \text{ fm}^{-1}$, reflecting the pionic enhancement. Here we fixed $g'_{\Delta\Delta} = 0.5$ [33] since the $g'_{N\Delta}$ dependence of the results is very weak. Around $q_{\text{c.m.}} \simeq 1.7 \text{ fm}^{-1}$, V_{eff} with these LM parameters is close to zero in the NN channel, but very attractive in the $N\Delta$ channel [13]. This attraction causes the pionic enhancement.

Before concluding the present analysis, we also considered effects of two-step contributions and isospin mixing in the 0^- state. The following two-step processes are evaluated by the computer code TWOFR [34]. (1) Excitation of the 0^- state via a 3^- , $0p_{1/2}^{-1}0d_{5/2}$ state [35] was added to the direct 0^- , $0p_{1/2}^{-1}1s_{1/2}$ excitation in the transition amplitudes. The OBDME for the 3^- transition was normalized to the described SM calculation, and the collective nature of the 3^- state was taken into account by a renormalization factor of 2 [35]. It was found that by including the two-step process the cross section was reduced not more than about 3% in the present momentum transfer range. (2) The two-step excitation via the nucleon pickup-stripping reaction, namely $(p, d)(d, p')$ and $(p, {}^2\text{He})({}^2\text{He}, p')$, was evaluated and the effect was found also to be a reduction of less than about 3%. Note that both proton-pickup-stripping and neutron-pickup-stripping should be considered simultaneously to reflect the isospin nature correctly. As for the isospin mixing, we do not have reliable calculations about the isospin mixing of the 0^- , $E_x = 12.80$ MeV state. If we take about 5% mixing of $T = 0$ states from a simple estimation by Barker [36], the mixing effect on the DWIA result was found to be a reduction of about 25%. This reduction can be overcome if we choose the smaller LM parameters, $g'_{NN} \simeq 0.6$ and $g'_{N\Delta} \simeq 0.3$.

In conclusion, our high-resolution measurement of $^{16}\text{O}(p, p')^{16}\text{O}(0^-, T = 1)$ has enabled us to search for a pionic enhancement at an intermediate energy of $T_p = 295$ MeV where the theoretical DWIA calculations should be reliable owing to the simple reaction mechanism. A significant enhancement has been observed around $q_{\text{c.m.}} \simeq 1.7 \text{ fm}^{-1}$ compared to the DWIA calculations with the SM wave functions and the local effective mass. The DWIA calculation employing the RPA response function with $g'_{NN} = 0.7$, $g'_{N\Delta} = 0.4$, and $m^*(0) = 0.7m_N$ reproduces the experimental data fairly well. Isospin mixing requires further enhancement of the pionic response function. The present analysis of our new measurement indicates the presence of the pionic enhancement in nuclei. However, further measurements for $q_{\text{c.m.}} < 0.9 \text{ fm}^{-1}$ as well as more detailed theoretical analyses are needed to confirm this indication.

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